2p(mix)

NASA TECHNICAL TRANSLATION NASA TT F-14474

ON THE ORIGIN OF LUNAR CRATERS

P. F. Sabaneyev

(NASA-TT-F-14474) ON THE ORIGIN OF LUNAR CRATERS P.F. Sabaneyev (Kanner (Leo) Associates) Jun. 1972 28 p CSCL 03B N72-32820 Unclas G3/30 43313

Translation of "O proiskhozhdenii lunnykh tsirkov," Vsesoyuzhnoye astronomo-geodicheskoye obshchestvo, Vol. 13, No. 20, 1953, pp. 7-20.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D. C. 20546 JUNE 1972

28p

Vsesoyuzhoye Astronomo-Geodicheskoye Obshehestvo, Moscow, V # 13(20), 1953, pp. 7-20.

ON THE ORIGIN OF LUNAR CRATERS

by

P. F. Sabaneyev

The singularity of lunar mountains is well known. The primary and most singular mountain formations of the moon are circular embankments -- craters, inside of which are located areas which are relatively lower than the surrounding surface, often having central elevations -- knolls, which are usually lower than the circular embankments. The circular embankments have steep inner and slanting outer slopes, up to 6 km in height. Indications of folding are sometimes noticeable in the structure of the embankments. In many cases the craters are surrounded by radially arranged light rays, which are very flat fills, up to 7.5 m thick and many times greater in their length than the diameter of the circular embankment. For instance, one of the rays of the crater Tycho has a length close to 3000 km.

In many cases, the listed basic indications are observed immediately in sharply expressed form. Often, however, separate construction elements of the formation are expressed weakly or are completely missing, and the presence of a crater is established only by remainders of the circular embankment. In these cases, the overall appearance of the landscape allows the supposition to be made that the effect of events taking place after the formation of the crater was felt here.

Irregularities in mountain forms on earth and on the moon show that craters arose as the result of some sort of completely different mountain-forming process. From here arose the problem of satisfactorily explaining the origin of the main mountainous forms of the moon. The most general circumstances for the formation of craters were properly noted in some hypotheses, but the absence of serious and widespread argumentation of the reasons weakened them.

It has been repeatedly noted that in a layer of loose substance lying on an even and solid base, with the fall of a clump, even one composed of the substance itself, formations will appear -- figures of the fall, possessing all the basic characteristics of lunar craters.

Figure 1 shows a photograph of a fall form -- a model of a lunar crater in a layer of cement -- attained by this method. In it the basic characteristics are easily distiguishable: the circular embankment, places of folding construction with steep inner and slanting outer slopes, the lowered inner area with its central elevation and radially thrown material outside the limits of the circular embankment. Some ejections, not located on the photograph, had a length which exceeded the diameter of the circular embankment by 9 - 11 times.

Figure 2 shows a photograph of two fall forms obtained in a layer of cement which is three times as thick. These

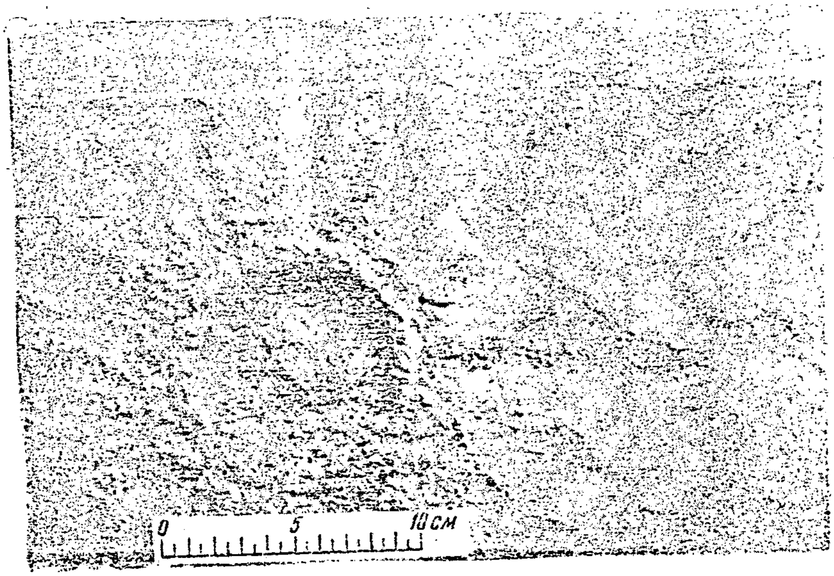

Fig. 1. Typical Model of Crater -- Fall Form in Cement Layer

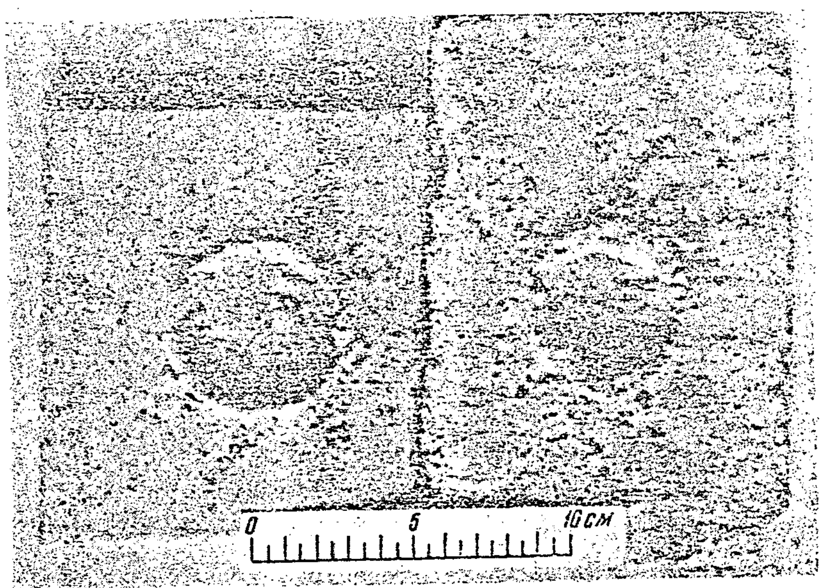

Fig. 2. Fall Forms in a Layer of Triple Thickness (by comparison with Fig. 1.) I -- in compacted, II -- in loose cement

forms have the same basic characteristic but some qualitative distinctions. The diameters of the circular embankments are smaller here, the central hillock was weakly developed, the inner slope of the circular embankment was almost vertical, there was a small number of ejections and their length did not exceed 5 - 6 diameters of the circular embankments. The fall forms depicted on Figure 2 were obtained in soils in differing states of compression. Figure 2, I was formed in a compacted layer of cement and Figure 2, II was formed in a layer of naturally loosened cement. The inner area of the first figure was almost horizontal and the radius of its conjunction with the circular embankment is small, as is the number of ejections. The second figure differs in the circular form of its cross section and somewhat larger number of ejections.

In this way, it is easy to obtain a combination of forms which is typical for the moon. Figure 3 shows a photograph of a combination obtained by throwing cement in a region on which the fall form is already formed in such a way so that the center of fall would be displaced from the noted circular embankment by a distance somewhat smaller than the intended radius of the new form. Fall form I (Figure 3) was formed by the first, and II was formed by the second. Examples of such a combination of craters on the moon are Teofil and Kirill, Isadore and Capella, and others.

In cases where clumps of cement are simultaneously dropped at a small distance from each other, a fall form with a straight partition appears (Figure 4). Similar formations in a clearly expressed form are not observed on the moon*.

It may be supposed that the so-called "straight wall" arose not as a fault but is a filled and eroded form of a similar type. This is pointed out by the remains of a characteristic combination of ends in the "straight wall" with an arc-shaped embankment.

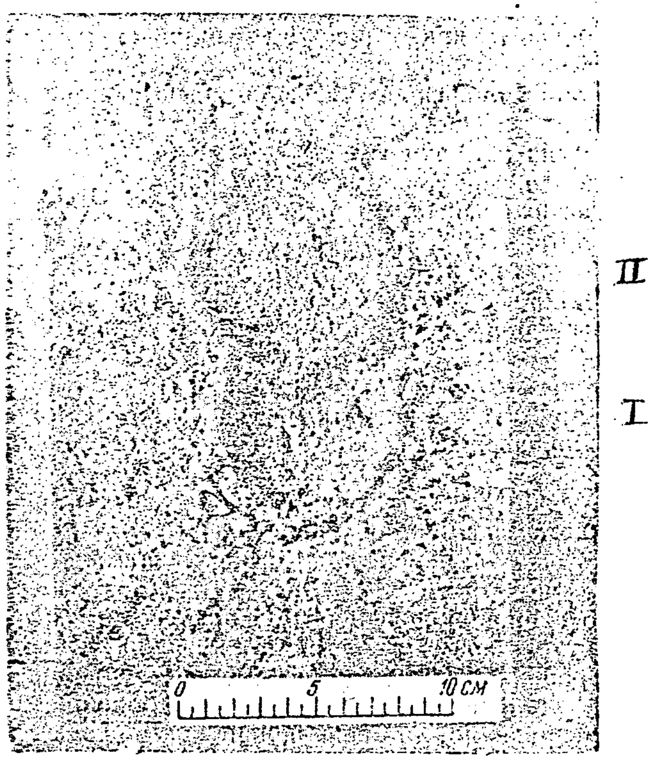

Fig. 3. Combination of Two Forms of Different Cement Droppings

I- Earlier Formed Drop Figure, II- Later Figure

* This opinion of the author is erroneous, since twin craters, separated by a straight partitioning embankment (for instance, to the west of Pitat and Gaurik) are not uncommonly encountered on the moon. (Ed.)

Fig. 4. Combination of Forms from Simultaneous Drop of Two Lumps of Cement

It is well known that tooth powder is distinctive in its property to sharply change its volume with compacting or loosening. The volume of packed tooth powder relative to that of loosened tooth powder is 1 : 1.5. When packed lumps of tooth powder are dropped into a layer of cement, a fall form occurs which is filled to the edges with the falling material (Figure 5). The falling material -- tooth powder -- lies in the inner area in a solid cracked mass. Ejections outside the limits of the circular embankment were small and chaotically arranged for the tooth powder. If the falling height for the tooth powder was increased, indications of a central hill with an uneven form appeared. This falling figure form is comparable to the form of the lunar crater Vargentine, which is the single one on the moon distinguishable by an example of a circular mesa.

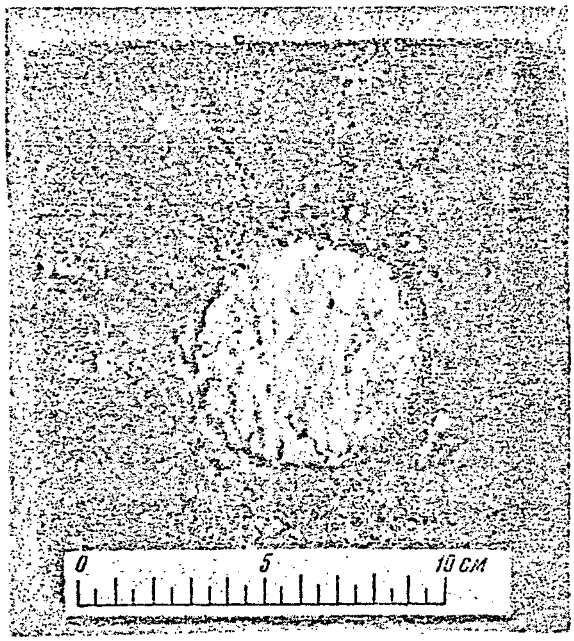

Fig. 5. Figure of a "Mesa" Type, formed through Dropping Compact Lumps of Tooth Powder in a Layer of Cement

It should be noted that the crater Vargentine is located on the visible portion of the moon in such a way that its surrounding situation is difficult to bring under study. This makes it extremely difficult to establish the reason for its appearance.

The similarity between the basic characteristics of lunar craters and falling figures attained by the method indicated are highly disputable. From hence comes the expediency for the detailed study of condition of formation of these figures for the purpose of establishing the most important circumstances under which the major mountain forms of the moon appeared.

The aim of this work was to explain the dependency of the form and dimensions of the falling figures on such factors as the physical properties and form of the falling substance, the angle of incidence, the properties of the soil, velocity and size of the falling mass.

1. Compactness of the falling substance. Experience has shown that the maximum similarity of falling forms with lunar objects is obtained when dropping a previously crushed substance, the appearance between the particles of which is insignificantly small. The regularity in the form of the falling figure is destroyed if the force of internal adhesion in the falling substance is increased. Simple packing of cement increases the adhesion between its particles very slightly, but already causes changes in the structure of the falling form: the height and degree of acuteness of its central hill are increased and the diameter of the circular embankment is decreased. Ejections of cement outside the circular embankment were absent in this case.

When cement lumps of uneven compactness were dropped, falling figures of irregular structure, often reminiscent of the form shown in Figure 4, were formed.

Lightly wetted calcined soda after drying formed lumps of slight strength and is not a flowing substance. Lumps of soda thrown into a layer of cement with force form falling figures of very different form. Large fragments are always observed close to the falling figure. The central hill is acutely peaked. The embankment never has the form of a perfect circle.

A steel ball thrown with force not only deforms the layer of cement but also the strong base of clay or sand beneath it. Cross sectional profiles of falling figures attained by this means are similar to cross sectional profiles of terrestial meteoritic craters and explosion funnels, but the fundamental form differs from profiles of lunar craters, which do not have a depression but an elevation, in their centers.

In all further experiments, only a free-flowing substance with a natural, even compactness were used as the falling material.

2. Form of the falling figure. Various geometrical figures, formed of cement, were dropped from the end of a glass plate into a layer of cement. The glass plate, rapidly moved by hand, was pulled from beneath the falling substance whose further dropping took place freely. Maximum similarity between the structure of falling figures and lunar craters was obtained while dropping round figures (sphere, hemisphere, cylinder, cone, round ellipsoid) under conditions so that their projections in the direction of falling had the form of a circle. The form of the falling figure formed as a result of dropping a round lens with its rib downward (Figure 6)

attracted attention to itself. Its distinguishing characteristics were the cross sectional elevation inside the circular embankment and ejections oriented in two mutually opposing directions. On the moon, the crater Copernicus is distinguished by this peculiarity. A. Vegener erroneously explains the formation of similar shapes by the inclined dropping of the substance [1].

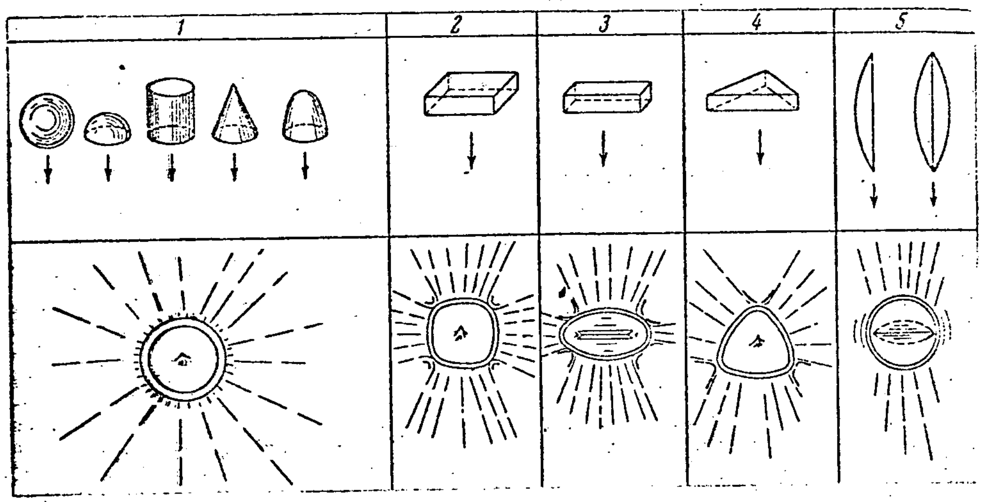

Fig. 6. Forms of Falling Bodies and Falling Figures Corresponding to Them

1 -- Round Figures, 2 -- Square Plate, 3 -- Elongated Plate, 4 -- Triangular Plate, 5 -- Lenses

In further experiments with dropping cement, only the form of a round semiellipsoid was used as the most technically convenient.

3. Angle of incidence. Two wooden rails, 8 mm in thickness were laid on a glass sheet and an even layer of

cement was filled between them. After this, a covering sheet of glass was laid on top and the surface of the cement layer was smoothed off. The ground, prepared in this manner for each experiment, was of identical thickness and compactness in all cases. After removing the covering glass, the sheet was set in an inclined position as shown in Figure 7. The cement layer remained stationary on the glass at an angle of β = 30°, and if the glass was replaced with a rough wooden board, the value for angle β could amount to 35°. The cement (10 g) was dropped vertically from position A, from a height H = 100 cm, and the minimum possible angle α have was equal to 55°. To accomplish dropping of the cement at a smaller angle, dropping was conducted from point A_1, in which the 10 g cement lump was given some velocity by hand along the horizontal. Accomplishment of falling at a small angle relative to the plane of the cement was eased by the relatively high value of angle $\alpha + \beta$.

Figure 8 shows a photograph of the falling figure attained at α_1 = 5°. Here there is no circular embankment. The falling cement created some small declinations in the ground and scattered, forming a tail in the direction of the incline of falling (shown by an arrow on Figure 8).

Figure 9 shows the falling figure at α_1 = 25°. The deformed ground has an oval form with indications of a central hill in this case. The ray-formed ejections are directed

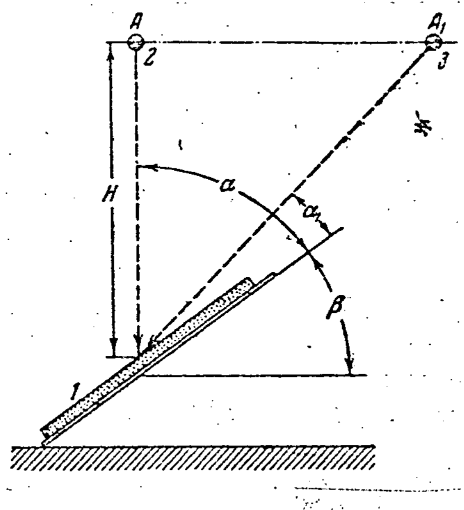

Fig. 7. Angles of Incidence
1 -- Cement Layer, 2 -- Cement Falling Vertically, 3 -- Cement Falling Obliquely

toward the slant of falling. Part of the rays form an angle less than 90° with a tangent to the oval embankment.

Figure 10 shows a photograph of a falling figure appearing $\alpha = 65^{\circ}$. By comparison with the preceding ones, its dimensions are considerably larger. The central hill in this case is sharply defined. The embankment is elliptical, with an axial relationship of 9 : 10. The larger axis of the ellipse coincides with the direction slant, the inner slope in the direction of falling slant is shallow and the slope opposite it is distinguished by its steepness. The ray-formed ejections are oriented toward the side of the falling slant. Ejections in the opposite direction are smaller and have the form of separate hummocks (the left part of the photograph).

Figure 11 shows the falling figure arising at $\alpha = 80^{\circ}$. Its overall structure is similar to the preceding ones, but its central hill is expressed even more clearly. Ejections

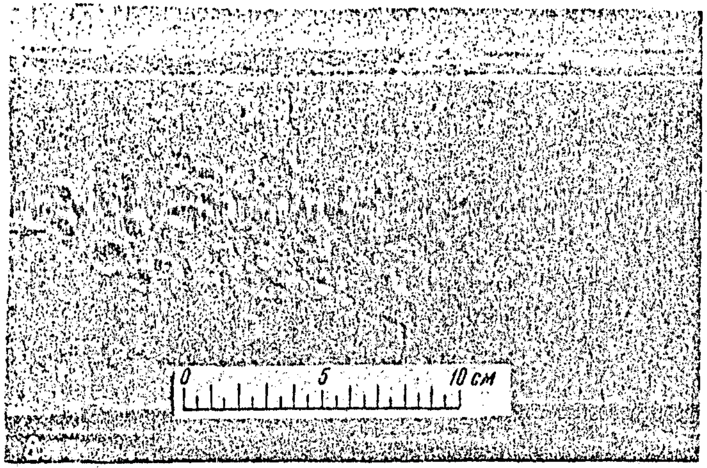

Fig. 8. Falling Figure at $\alpha_1 = 5^{\circ}$

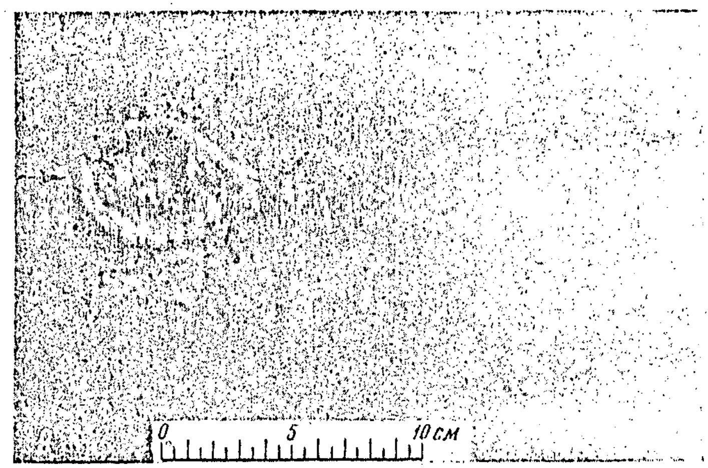

Fig. 9. Falling Figure at $\alpha_1 = 25^{\circ}$

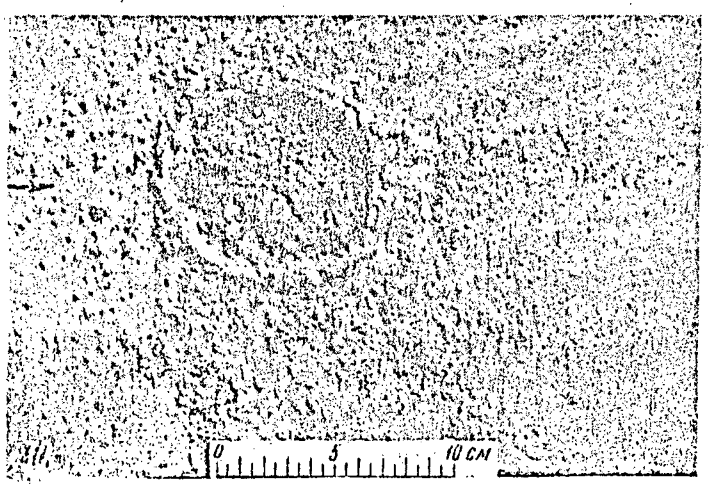

Fig. 10. Falling Figure at $\alpha = 65^{\circ}$

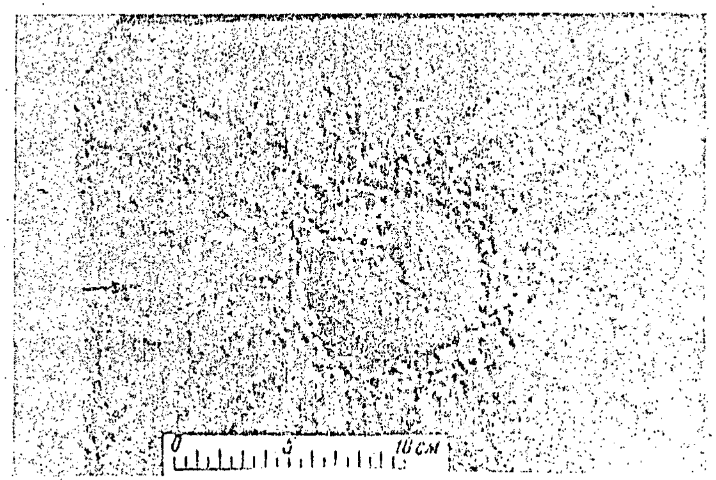

Fig. 10. Falling Figure at $\alpha = 80^{\circ}$

of the ray-like structure in all directions, but the majority of them are oriented toward the falling slant. Ejections have the greatest length in this same direction.

Falling figures with $\alpha < 90^{\circ}$ and similarity of all conditions of formation are not distinguished by steadiness of their dimensions and perfection in form. Only a perfectly vertical fall yields a profile structure whose cross section is perfectly symmetrical in all directions.

Forms similar to those shown in Figures 8 and 9 are not observed on the moon. Similarities with lunar forms occur only with larger values of angle α.

4. Compactness of the ground. Increasing the force of bonding between the particles of ground substance has an essential influence on the structure of the falling figure (Figure 12). With equal quantities of falling substance and identical falling velocities, the diameter of the circular embankment is smaller, the inner slope of the circular embankment is steeper, the depth of the inner area is shallower and ejection consists primarily of dropped material in packed soil. Generally, ejections outside the limits of the circular embankment may consist either of the base soil material or of the falling substance. In both cases, ejections are located radially. Ejections of the base material are usually less broken up and have great length. They form piles and accumulations in the immediate vicinity of the circular embankment.

Ray-formed ejections of the base material are more or less unbroken chains of lumps and spots. Rays of the fallen material are unbroken flat strips of finely dispersed substance.

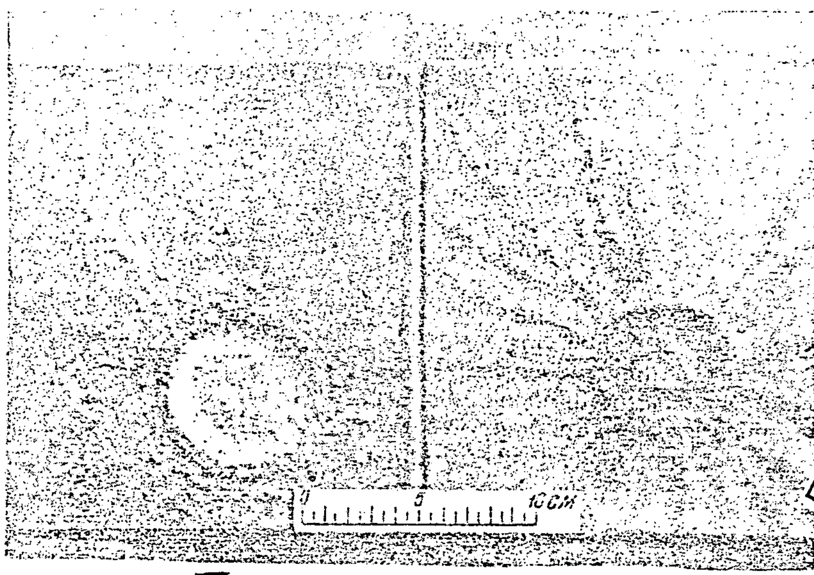

Fig. 12. Falling Figures in Soil of Varying Compactness
I -- Gypsum Dropped in a Loose Layer of Cement, II -- Cement Dropped in a Packed Layer of Gypsum

5. Thickness of the ground layer. Figure 13 shows a change in the cross section of a falling figure with a change in the thickness of the ground layer. The change in the basic dimensions of the profile in dependence on the thickness of the ground layer is shown in Figure 14.

With no other changes in all the conditions of falling figure formation, the diameter of their circulam embankment increases with a decrease in the thickness of the ground layer. The depth of the inner area increases with the thickness of the ground. The central hill is formed in all, but with a

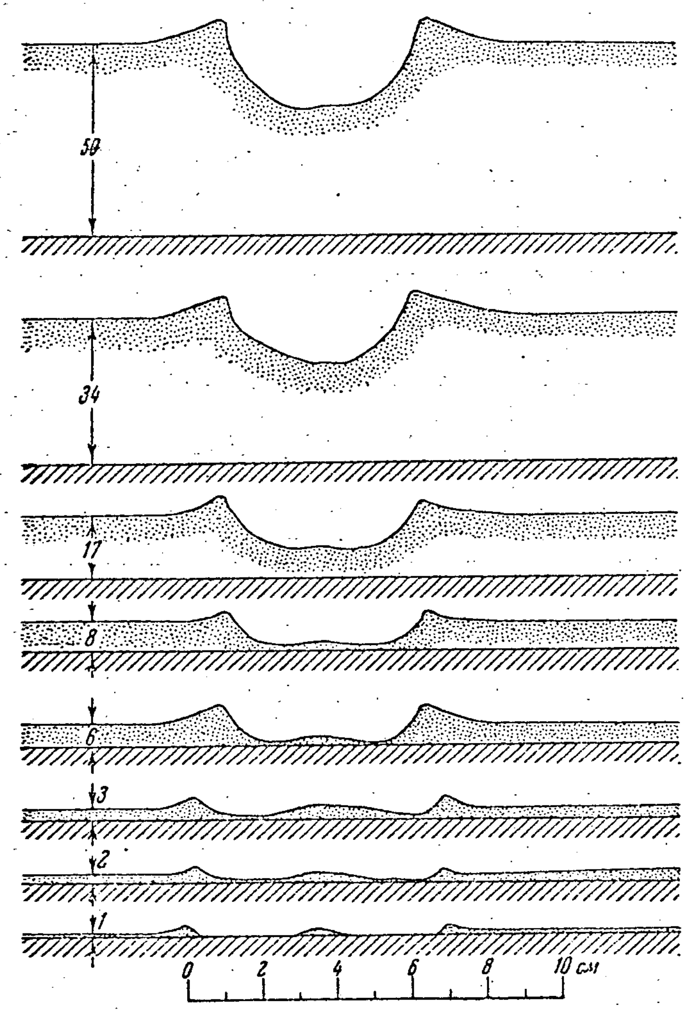

Fig. 13. Cross Section of Falling Figure at Varying Ground Layer Thicknesses

great ground thickness, it is in a rudimentary state and hardly distinguishable. With a decrease in the thickness of ground, the dimensions of the hill grow and it acquires the character of a basic construqtion element of the falling figure. Experience showed that with great ground thicknesses, the quantity of ejections is small and they consist of the ground material.

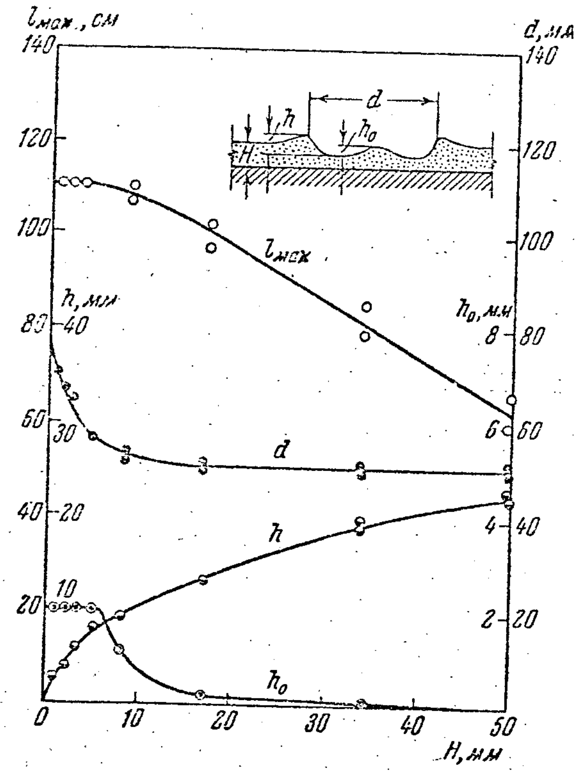

Fig. 14. Changes in the Diameter of the Embankment (d), Its Height (h), Height of the Central Hill (h_o) and Distance of Ejections (l_{max}) and Dependency on Thickness of Ground

At slight ground thicknesses, the converse is observed: the quantity of eject material grows and the content of fallen substance in it also increases.

6. Falling velocity. To study the dependency of the formed figure on the falling velocity, cement was dropped from various heights (from 10 to 300 cm). Dropping from a greater height was hindered by the beginning breakup of the cement lump which occurred due to the resistance of air. A dependency of the diameter of the circular embankment d, the area of the crater f, and the length of ejection l_{max} (counting from

the edge of the circular embankment) on the calculated velocity of falling is shown in Figure 15. On inspection of Figure 15, it is evident that an increase in the diameter of the circular embankment and area of the crater occurs with gradual slowing with an increase in falling velocity. Length of ground ejections increases proportionally to an increase in falling velocity.

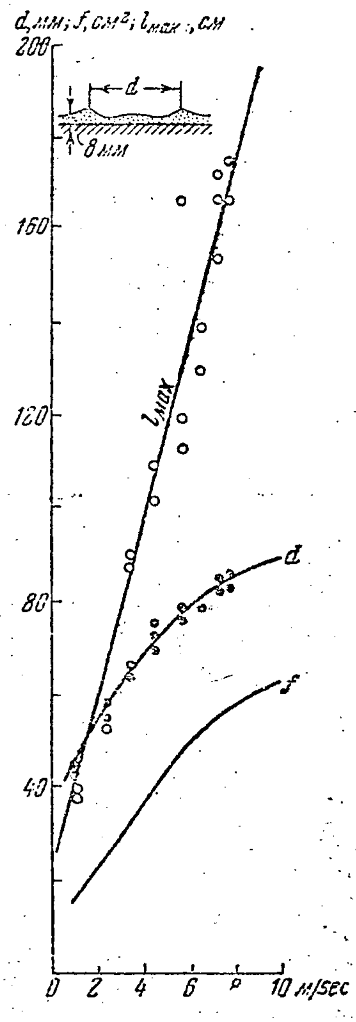

Fig. 15. Changes in the Basic Geometric Characteristics of Craters Depending on Falling Velocity

It is necessary to note the fact that the velocity of separate ejections increases by comparison with the velocity of falling. Comparison of the velocity of ejection v_B and the velocity of falling v_n depending on the height of falling H are presented in Table 1. Velocity of ejections was computed according to the formula

$$v_{в} = \sqrt{\frac{l_{max}\, g}{\sin 2\theta_1}},$$

where θ_1 -- angle of elevation of the ejection stream above the horizon, taken as = 45°,

g -- acceleration of the force of gravity.

Table 1

Velocity of Ejections and Velocity of Falling

H (м)	$v_{п}$ (м/сек)*	$v_{в}$ (м/сек)*	$n = \frac{v_{в}}{v_{п}}$
0,10	1,4	2,1	1,50
0,25	2,2	2,4	1,10
0,50	3,1	2,7	0,88
1,00	4,4	3,2	0,73
1,50	5,4	3,5	0,65
2,00	6,3	3,8	0,60
2,50	7,0	3,9	0,56
3,00	7,7	4,1	0,53

* m/sec

The actual velocity of falling is less than the velocity of v_n presented in Table 1 due to the resistance of air. With an increase in the velocity of falling, the velocity of ejections increases, but dispersion of the ejected substance grows, increasing the resistance of air. Under experimental conditions, θ_1 always varies from 45°. This indicates that the actual initial velocity of ejections always exceeds the table values v_B. On the basis of this, it is possible to suppose that the actual value of $n = \frac{v_B}{v_n}$ is also greater than that on the table.

7. Quantity of the falling substance. The dependence of the diameter of the circular embankments, the area of the falling form and the limiting distance of ejections on the quantity of the falling substance was studied at falling velocities of 3.1 - 5.4 m/sec.

All three elements increased with an increase in the quantity of falling substance, and the area f increased in direct proportion to the quantity of falling substance.

For study of the trajectory of the ejections on the layer of cement, vertical screens made of heavy fleecy paper were erected (strictly radially to the intended center of the falling figure). After the drop of the cement, prints of the cross section of the falling figure and the trajectory of the ejections showed on the screen (Figure 16). It becomes apparent that ejections originate from the inner area of the falling figure, not far from its center, where they have the maximum value. The velocity of the ejections decreases and has its smallest value at the very edge of the circular embankment. The angle of lift of the ejection trajectories for the given formation was uniform. With an increase in the falling velocity and the quantity of falling substance, the angle of trajectory lift decreased and it began to approach the angle of the natural slope of the material, amounting to 45°.

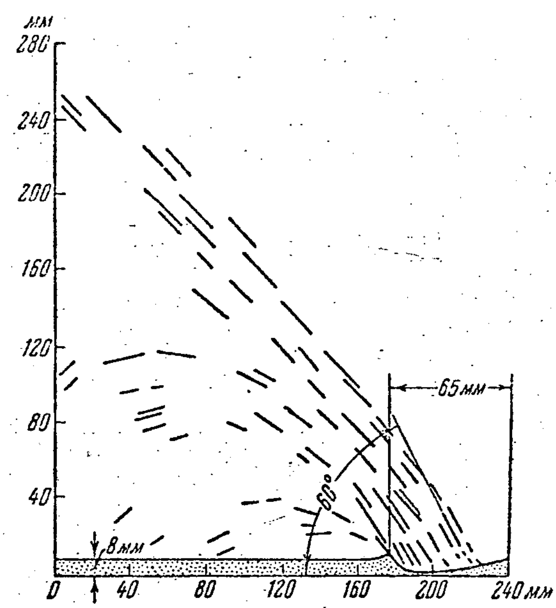

Fig. 16. Direction of Ejections (Vertical Section)

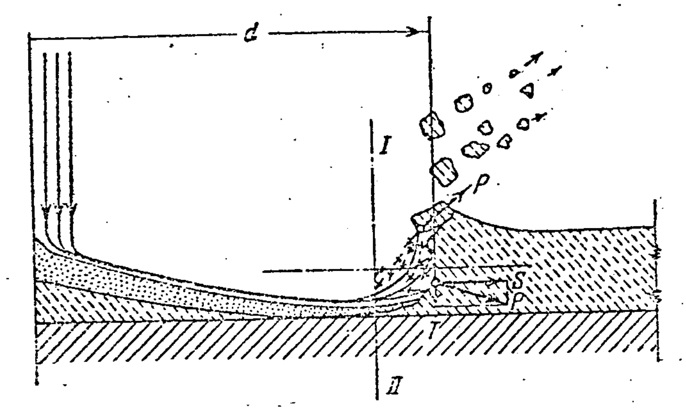

Fig. 17. Diagram of Crater Embankment Formation

After dropping cement on a plate made of glass, likenesses to a central hill were formed on it and a layer of cement on another plate next to it received deformation, similar in structure with the circular embankment of the falling figure. This experiment shows that the formation of a circular embankment and the appearance of ejections outside its limits can be explained exclusively by the action of a horizontal, radially located stream of falling substance. There is no basis for comparing the process of lunar crater formation, as is sometimes done, with wave motion of a liquid when a solid body falls into it.

The diagram of falling figure formation is shown in Figure 17. The solid stream of falling particles, packing and moving the layer of cement, forms a depression in it. Part of the falling material forms the packed central hill, along which the remainder of its particles slide radially, forming a circular chamber in the ground. The stream of particles causes some pressure P on the inner surface of the circular chamber, due to which its upper edges break off in quadrant I. The fragments appearing during this form ejections, accumulation and piles near the circular embankment.

In quadrant II, the force of pressure P breaks down into two components: T -- packing the ground and S -- moving it and increasing the diameter of the circular embankment. After striking the wall of the circular chamber, the falling material settles onto the bottom of the formation. The force of the pressure weakens according to the consumption of the falling substance and the increase in the internal surface. The increase in diameter d ceases at the moment equilibrium is established between the force of pressure P and the force of resistance determined by the strength of the soil. Ejections of the falling substance outside the limits of the circular embankment can occur with great power of its stream and slight thickness of the soil, when heavy breakage of the lip of the circular chamber occurs. Extensive scattering of the falling material also takes place with an increase in the strength of the soil, when the lip of the circular chamber is weakly developed or is missing altogether.

Conclusions

Results of experiments presented allows the following basic suppositions to be made on the origin of lunar craters:

1. Craters arose as a result of falls by compact, uniform, definitely round masses of loose material. It may be allowed that the form of masses falling on the surface were also lenticular.

2. The surface of the moon is covered with a material distinguished from deeper rock by a decreased strength.

3. The significant dimensions of craters and the great length of their ejections first of all point up to the fall of large masses of substance and also cannot be reviewed as undisputable evidence of very high velocities of falling.

4. The round form of the craters points up to the vertical fall of the substance. Ovality of the circular embankment, imperfection in the internal structure of the craters and orientation of the ejections in one direction testify to the fact that it was a case in which the substance fell at some (but sufficiently large) angle to the horizontal. All this points out the fact that the fall took place primarily due to the effect of the lunar gravitational field.

In a vertical fall, the velocity caused by the lunar gravitational field cannot exceed 2400 m/sec. If it is allowed that fall took place at an angle of no less than 60°, velocity could not exceed 2750 m/sec. These velocities are not great enough for an explosion to be formed at the point of falling, which would require a velocity of 4000 - 6000 m/sec. [2].

5. In only one of the many thousand instances can simultaneous falling of two closely located masses of substance on the surface of the moon be presumed. Traces of sequential falling, one after the other on the moon, are often encountered. This testifies to the great variation of falling masses in space before they were attracted by the moon. The grouped location of craters can testify to the attraction by the moon of several masses moving in one direction.

These reasons allow assumption on the existance in the past of a significant number of satellites, besides the moon, of small mass near the earth, whose orbits were close to the orbit of the moon, which favored their falling to the surface of the moon and led to the formation of the lunar cirques and craters.

It can be supposed that craters might be discovered on some satellites of other planets, and perhaps on Mercury.

There is no basis for the assumption that mountain formations similar to lunar craters might have arisen on earth in the past, even if similar stratographic conditions existed in the external layers of the terrestial crust. The mechanism of the process of forming craters of this type, as is represented for the moon, could not have existed on the earth due to the high velocities of falling, in the order of 11,100 m/sec.

The change in the aggregate state of the falling substance from solid to gas in the place of its falling [2] could not help but destroy its stream, horizontal and radially located along the surface of the earth and the wholeness of deep rocks. Under earth's conditions, mountain forms must have been formed some other way, fundamentally differing from those observed on the moon.

Rostov-on-the-Don, June 1951

Bibliography

1. A. Vegener, The Origin of the Moon and Its Craters, Gosizdat, 1923.

2. K. P. Ctanyukovich and V. V. Fedynskiy, On the Destructive Effect of Meteor Strikes, DAN USSR, 57, No. 2, 1947.

Editorial Note

Experiments on artificial reproduction of lunar craters have already been conducted repeatedly (see A. V. Khabakov "On the Basic Questions of the History of the Development of the Surface of the Moon" Zap. Vses. Geogr. O-va, v. 6, 1949, p. 147). The experience of P. F. Sabaneyev is interesting in the fact that he succeeded, in a number of cases, in obtaining a central hill out of freely flowing material, while at the same time the experiments of A. Vegener led the latter to the conclusion that a hill is formed only in the presence of a closely lying hard base and is the remainder of the solid rock left intact in the epicenter (see Khabakov, p. 159). Further, the experiments of P. F. Sabaneyev, illustrated by Figures 1, 10, 11 and 12 in which craters and rings of rays are simultaneously formed, are very interesting. Vegener did not succeed in obtaining rays and craters with one single strike, and it was necessary to first empty out the powder so as to form the rays, and then strike with a compact mass at the same point, to create the crater (Khabakov, p. 174).

Translated from the original Russian by LEO KANNER ASSOCIATES, P. O. Box 5187, Redwood City, California 94063, (415) 365-3046, February 1972